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Monterey, California

ANNUAL SUMMARY OF BASIC RESEARCH
THERMOACOUSTIC HEAT TRANSPORT: 1992

ANTHONY A. ATCHLEY

NOVEMBER 1992

Annual Summary for Period October 1991 - September 1992

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Anthony A. Atchley

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Physics Department
Naval Postgraduate School
Monterey, CA 93943

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SUMMARY OF PROGRESS

Our major research efforts in thermoacoustic heat transport were concentrated in two areas during FY 1992: 1) a standing wave analysis of the low amplitude performance of thermoacoustic prime movers both below and above the onset of self-oscillation and 2) a study of finite amplitude standing waves in both harmonic and anharmonic tubes. In addition to these areas, FY 1992 research efforts also included the investigation of heat driven refrigerators and preliminary work on investigations of thermoacoustic engines with laser Doppler anemometry.

1) Standing Wave Analysis of the Low Amplitude Performance of Prime Movers

A. Below Onset of Self-Oscillation

The purpose of this project is to develop a method of analyzing the performance of prime movers and comparing the predictions to experimental results. This analysis, motivated by Swift,[1] assumes that the acoustic pressure and velocity can be described in terms of a standing wave throughout the prime mover and is not limited by either the small boundary layer or short stack approximations. It falls somewhere between the two methods of analysis discussed in Ref. 1. It is more general than the short stack, boundary layer approach but not as general as the fully numerical approach. It maintains the conceptual simplicity of the former and allows one to appreciate the need for the later. The discussion that follows summarizes a complete discussion of the analysis found in Ref. 2.

The results of the analysis are shown for the first longitudinal mode of a helium filled prime mover in Fig. 1. The figure, a graph of the reciprocal of the quality factor of the prime mover Q versus the temperature difference applied across the prime mover stack, corresponds to a mean gas pressure of 170 kPa. The solid line indicates the results of our standing wave analysis. For comparison purposes, the results of the porous medium analysis (discussed in Ref. 3 and the result of our FY 1991 research) is included, the dashed lines. It is evident that the standing wave analysis provides a better fit to the 170 kPa data than does the porous medium approach. However, the two techniques do more-or-less equally well at higher mean gas pressures. There is a tendency for the standing wave technique to under predict the attenuation, which is proportional to $1/Q$, at zero temperature difference.

The data presented in this figure are a composite of individual data sets recorded at different times with (slightly but inevitably) different mean temperatures and mean gas pressures. The spread in the data is indicative of the uncertainty. Sources of experimental errors are uncertainties in mean temperature, temperature difference, mean gas pressure, the positions of the prime mover elements, and the geometry (plate spacing and perimeter) of the heat exchangers and prime mover stack. The net effect of these error sources is illustrated using the results presented in Fig. 1. The predictions were recalculated including each individual error source and the deviations between the new and the original calculations found. These individual deviations were added together to arrive at the total deviation. In Fig. 2, the solid line represents

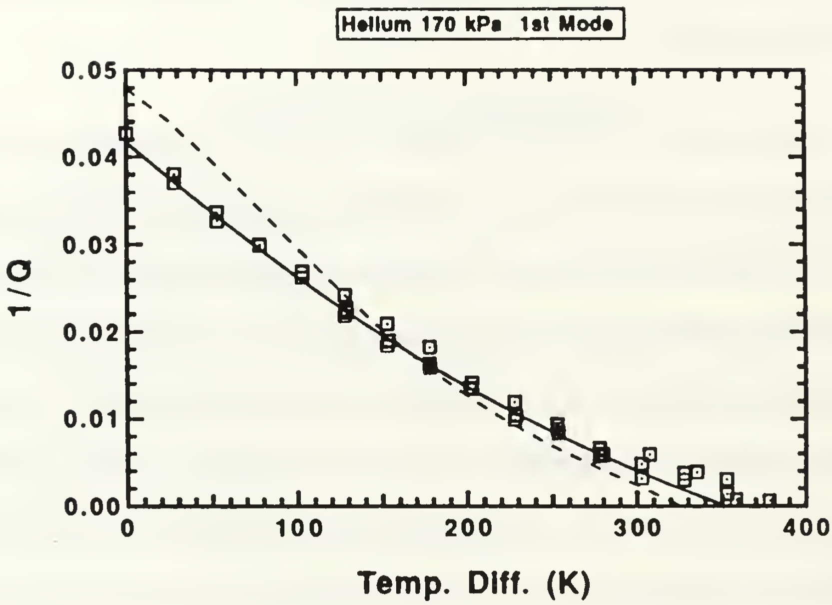


Figure 1

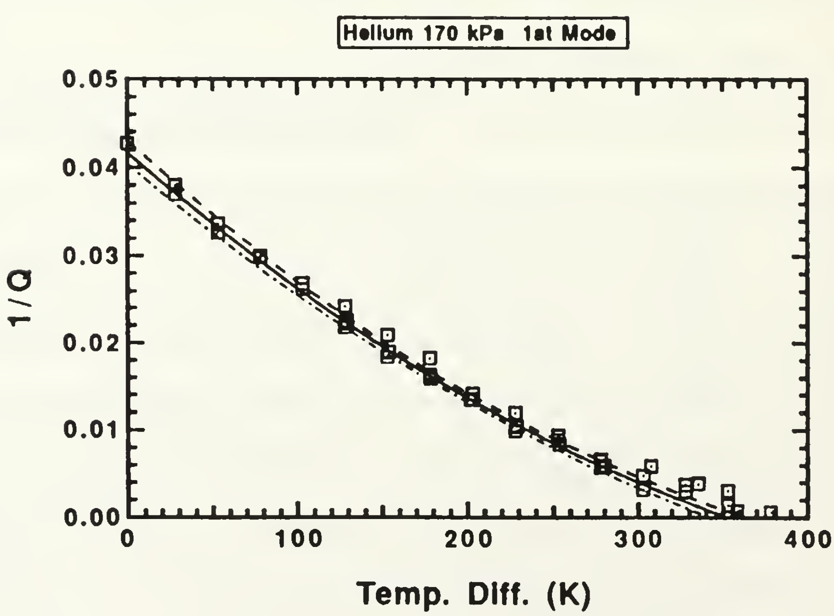


Figure 2

the original calculation as presented in Fig. 1. The dashed (dash-dot) line represents the original calculation plus (minus) the total deviation due to errors in mean temperature, temperature difference, mean pressure, and positions and perimeters of the elements. Most of the data points fall within these limits, though there are some exceptions, especially near onset. These errors introduce an uncertainty in the temperature difference required for onset of approximately 20 °C.

The calculations discussed up to this point have been somewhat involved. The heat conduction equation is solved numerically, taking into account the temperature dependence of the thermal conductivity of the gas and stainless steel stack plates. An example of the distribution of the temperature and temperature gradient is shown in Fig. 3 for a temperature difference of 350 K. It is seen that the temperature (solid line) is almost linearly distributed along the stack. The temperature gradient (dashed line) varies by approximately 20% over the length of the stack. This temperature distribution is used to find the spatial dependence of the temperature dependent variables, to allow numerical integration along the stack.

A natural and important question arises. How much can these procedures be relaxed and still obtain reasonable results? Providing, at least, some of the answers to this question is an important result of this work. Neglecting the thermal conductivity of the gas has negligible effect on the results of the calculations. Assuming that the temperature gradient is constant along the stack (and simply equal to the temperature difference divided by the length of the stack) has only a slight effect. It pushes the onset temperature higher than that predicted by the full calculation by about 5 °C at 170 kPa. The difference

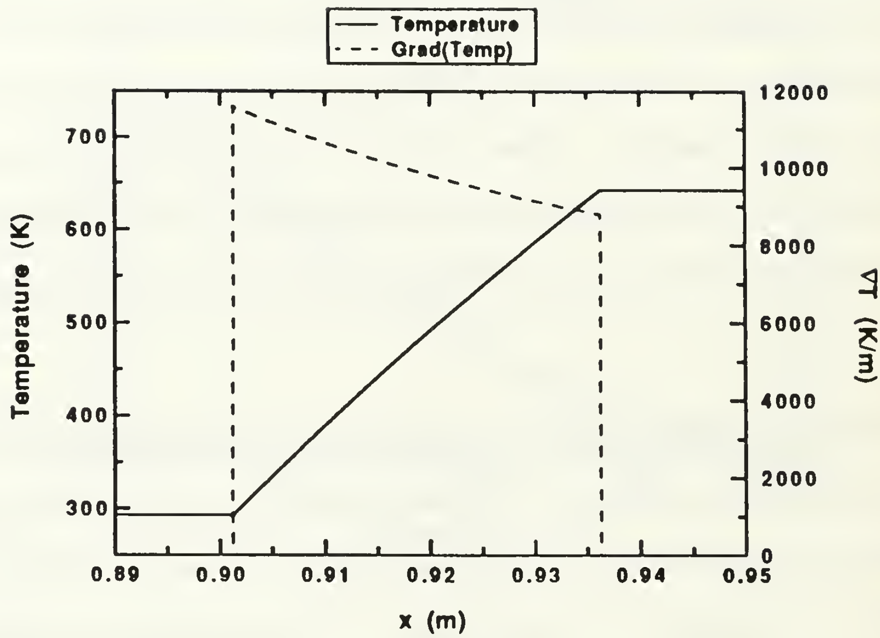


Figure 3

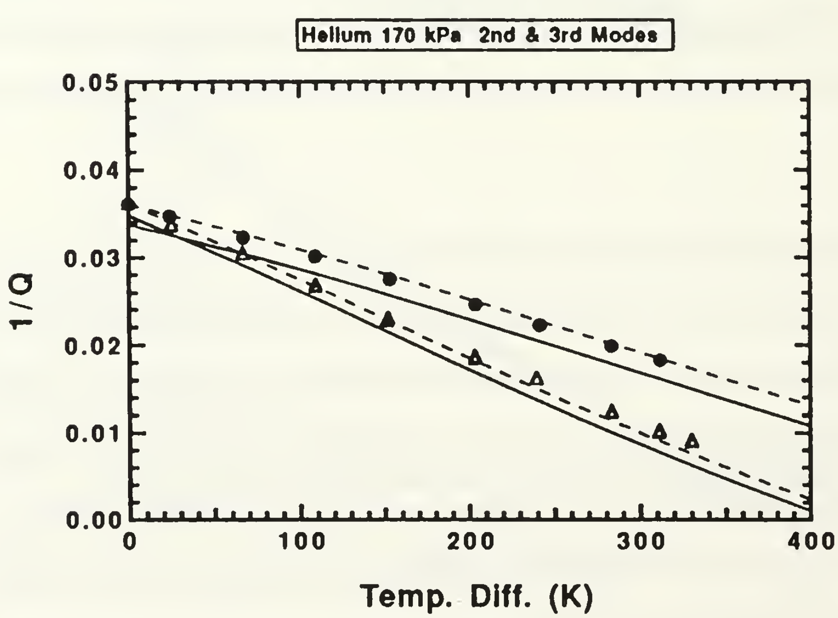


Figure 4

diminishes as the mean pressure increases, virtually disappearing at 500 kPa. All of these simplifications are probably tolerable unless one requires very precise results.

A much more drastic simplification is to assume a constant temperature gradient and use the average stack temperature to calculate the thermophysical properties of the gas along the entire length of the stack. This assumption greatly simplifies the analysis, removing the need for numerical integration. At 170 kPa, this assumption reduces the predicted onset temperature by approximately 10 °C. However, at 500 kPa the situation is somewhat worse. In this case, the predicted onset temperature is reduced by approximately 25 °C. Therefore, while this assumption certainly has computational advantages, it does not produce very accurate results near onset. However, for temperature differences sufficiently below onset, the differences between predictions based on this assumption and the full calculation are likely tolerable.

To test our ability to predict the Qs of higher modes, we measured the Q as a function of temperature difference for the second and third modes of the prime mover. The results for a mean gas pressure of 170 kPa are shown in Fig. 4. The solid lines show the predictions of the standing wave analysis. As is the case with the fundamental mode, the analysis tends to under predict 1/Q. However, the overall trends match well. The dashed lines are the results of correcting the predicted values by adding to them the differences between the predicted and measured results at zero temperature difference. The corrected prediction agrees quite well with the data, especially for temperature differences well below onset.

B. Above Onset - During the Initial Growth of Oscillations

The comparisons presented above were made for a prime mover operating below onset. Below onset the temperature distribution in the stack is governed by thermal conduction through the plates. Under these circumstances the analysis gives good agreement with the data. However, above onset, the steady state acoustic pressure amplitudes are typically 1 - 10% of mean pressure. At these high amplitudes the temperature distribution in the stack is significantly influenced by the acoustic heat transport. It remains to be seen how well the present analysis predicts the large amplitude performance of a prime mover operating above onset. Of course, given the actual temperature distribution in the stack, there is no reason to expect that the standing wave analysis would break down. However, if one is going to go the effort of accurately calculating the temperature distribution under large amplitude conditions, then one might as well as do a fully numerical solution to the problem. However, it is difficult to gain intuition from a fully numerical approach unless one has a fair amount of experience with either thermoacoustics or numerical calculations. It is suggested that, because it is conceptually relatively simple, the standing wave analysis is a good alternative.

Low amplitude conditions do exist in prime movers above onset - during the initial build up of the oscillations. By measuring the rise time of the buildup, Q can be determined and plotted on the same graph with the below onset Qs determined from frequency response measurements. Such data are shown in Fig. 5, for a helium filled prime mover at a mean gas pressure of 376 kPa. In contrast to the earlier figures, this time we plot Q, not 1/Q, vs. ΔT. In this representation, onset is clearly defined by the rapid divergence of Q. The solid

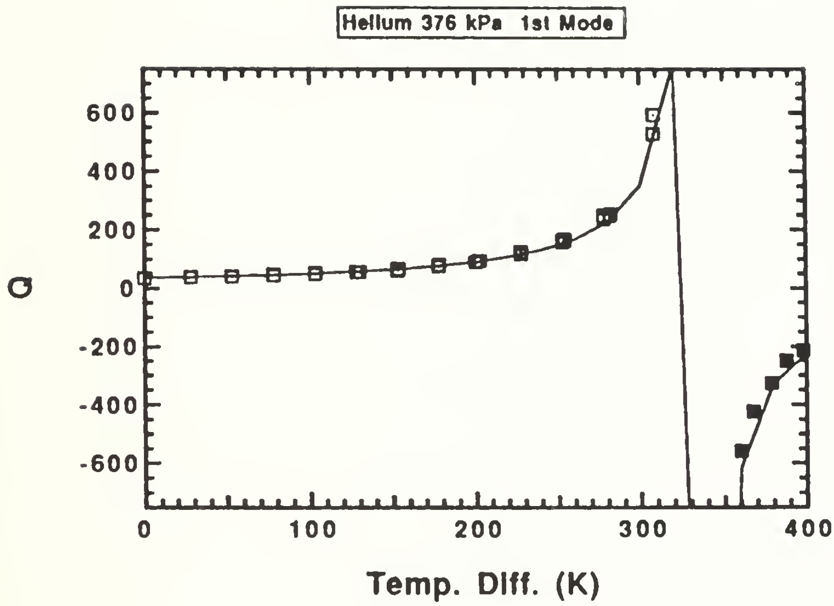


Figure 5

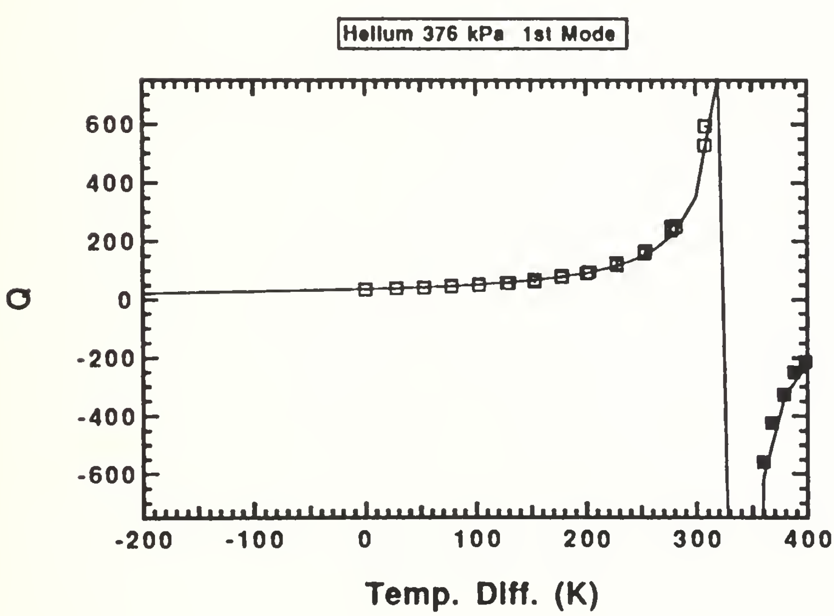


Figure 6

line is the result of the standing wave analysis. The agreement is quite good over a 400 K span of ΔT. (It is worth pointing out that there are no adjustable parameters in the model.) Therefore, the conclusion drawn earlier, that the standing wave analysis does a good job of predicting low amplitude prime mover performance, is valid both above and below onset.

C. Below Onset Revisited

Practically all thermoacoustics research has concentrated on the large amplitude regime, the emphasis being on industrial and commercial applications of heat engines. However, Fig. 5 points out another potential use for thermoacoustic prime movers - but below onset. Notice that the quality factor of the resonator (after all prime movers are resonators) can be adjusted over a range spanning at least one order of magnitude. This ability might be useful in applications requiring high Q acoustic resonators, such as in photoacoustic spectroscopy.

Consider Fig. 5 once again. What happens to Q if ΔT is negative? It goes down. This point is illustrated in Fig. 6, the only difference between it and Fig. 5 being that the calculations have been extended to negative values of ΔT. For this prime mover, Q can be reduced by a factor of approximately 2 from its value at $\Delta T = 0$ by applying a ΔT of -200 K, achievable with liquid nitrogen. This reduction may not be all that impressive, but on the other hand this prime mover is not optimized for the purpose of *reducing* Q! However, if the stack was optimized (for instance, by using a larger stack surface area to compensate for the limited available temperature difference), there is no reason why the Q could not be reduced further. Suppose the Q were reduced to nearly zero. In this limit, the prime mover stack can be thought of as a termination with a very low reflection coefficient. In the limit of low reflection coefficient, standing waves becomes traveling waves, and our standing wave analysis will probably break down. But one could use a technique such as the counter-propagating plane wave method discussed in Ref. 3 to analyze the problem. In principal, such a termination could be compact, compared to typical wedge shaped, steel wool terminations which are one or more acoustic wavelengths long.

A thermoacoustic termination transitions standing wave thermoacoustics to traveling wave thermoacoustics, such as originally investigated by Ceperley.[4-6] In fact, Ceperley measured gains less than 1 in a traveling wave engine.[4] However, most thermoacoustics research is aimed at producing gains greater than 1. So, it appears that the possibility of enhancing loss has been discarded as parasitic. The enhancement of the performance of thermoacoustic refrigerators by using mixtures of both standing and traveling waves in the same engine is a topic of current interest.[7,8] The use of a thermoacoustic termination may be of potential benefit to this work.

2) <u>A Study of Finite Amplitude Standing Waves in Both Harmonic and Anharmonic Tubes</u>

In practical thermoacoustic engines, standing waves having peak acoustic pressure amplitudes on the order of 10% of ambient pressure are common. Our prime mover research has shown that the waveforms of the acoustic oscillations can be highly nonlinear.[9] The resultant generation of harmonics of the fundamental frequency takes energy out of the fundamental mode. Because typical thermoacoustic engines are designed to operate optimally at the fundamental frequency, the transfer of energy to higher harmonics represents a parasitic loss. Some questions arise. Can the nonlinear waveforms be predicted? How much of the energy input to the fundamental is transferred to higher modes? Is there a way to prevent this loss? The discussion that follows is a condensation of a complete analysis found in Ref. 10.

The waveforms observed in our prime mover[9] are very similar to those observed by Coppens and Sanders in a rigid tube driven with a piston source at one end.[11,12] This similarity suggests that waveforms in the prime mover could be modeled in the same way. However, there are at least two significant differences between prime movers and simple standing wave tubes. First, the drive mechanism is completely different. Also, in typical standing wave tubes, the dispersion is small enough that the overtones of the tube are very nearly harmonically related. This means that the harmonics generated in the acoustic field through nonlinear mechanisms also "drive" each of the modes of the tube at their resonance frequencies, setting up standing waves for each mode. However, the geometry of prime movers is such that this does not necessarily happen. Finding that finite amplitude standing waves in anharmonic, or detuned, tubes has received little attention in the literature, we decided to initiate our investigation of nonlinear oscillations in prime movers by first studying nonlinear oscillations in harmonic and anharmonic tubes, with the goal of answering the questions raised earlier.

Observations of finite amplitude standing waves were made in closed-closed, rigid, thick-walled aluminum tubes driven at resonance by a sinusoidally oscillating piston at one end. Three different tubes were used: one with constant cross section, one with a reduced cross section and one with an enlarged cross section, referred to as Tubes #1, 2 and 3, respectively. In Tube #2, the inner diameter is reduced by about 20% for approximately 13% of its length. In Tube #3 the inner diameter is enlarged by 20% for about 31% of its length. In both Tube #2 and #3 the change in cross section is symmetric with respect to the midpoint of the tube. The effect of the change in cross section of the tubes is to break up the harmonic relationship between the resonance frequency of the fundamental and higher modes. Tables 1 and 2 summarize the acoustic properties of the tubes. Table 1 contains the measured shift in resonance frequency of the first five mode of tubes #2 and #3 relative to the Tube #1. Table 2 shows the harmonicity of the tubes, which is defined by F_n/F_1, where F_n is the resonance frequency of mode n and F_1 is the fundamental resonance frequency.

The acoustic waveforms were measured in each tube as a function of the acoustic pressure amplitude. This amplitude will be represented by the dimensionless quantity[12]

$$\frac{1}{2}\frac{M\beta}{\alpha_1/k_1} = M\beta Q_1 = \frac{P_1}{\gamma P_o}\beta Q_1 , \tag{1}$$

where M is the acoustic Mach number, $\beta = 1.2$, P_1 is the peak pressure amplitude of the fundamental component, P_o is the ambient pressure and Q_1 is the quality factor of the fundamental mode. This quantity measures the ratio of waveform strength ($M\beta$) to fractional loss per wavelength (α_1/k_1), and is referred to as the *strength parameter* (s.p.).

Figure 7a shows the pressure waveform generated in Tube #1 at s.p. = 1.1. Notice the discontinuity formed by the shock wave traveling back and forth in

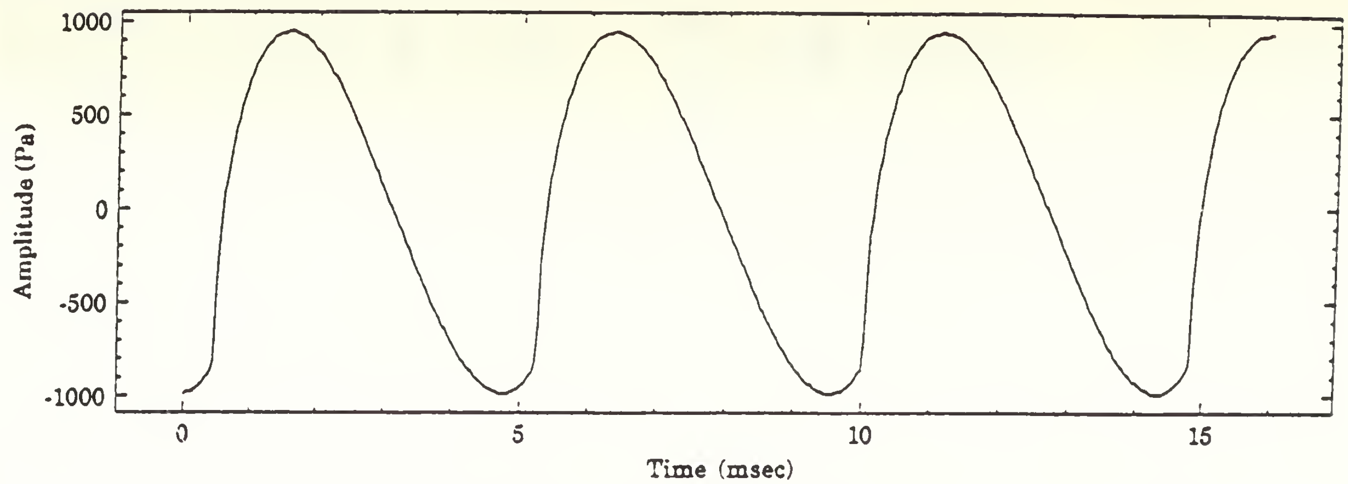
Table 1: Measured and Calculated frequency shift in percent relative to Tube #1. $(F_{res} / (F_{res})_{\#1} - 1)*100$

mode	1	2	3	4	5
<u>Tube No. 2</u>					
Measured	-7.5	6.0	-6.2	3.8	-3.5
Eqn. (13)	-8.6	5.3	-5.9	4.0	-2.9
<u>Tube No. 3</u>					
Measured	10.9	-7.3	0.90	2.6	-2.4
Eqn. (13)	10.14	-6.5	1.10	1.8	-2.8

Table 2: Measured harmonicity. (F_n / F_1)

mode	2	3	4	5	6	7	8	9
Tube No.1	2.00	3.01	4.01	5.01	6.01	7.01	8.02	9.02
Tube No.2	2.31	3.10	4.56	5.32	6.68	7.63	8.70	9.94
Tube No.3	1.70	2.76	3.70	4.42	5.52	6.40	7.15	8.28

(a)


1000
500
0
-500
-1000
Amplitude (Pa)
0
5
10
15
Time (msec)

(b)

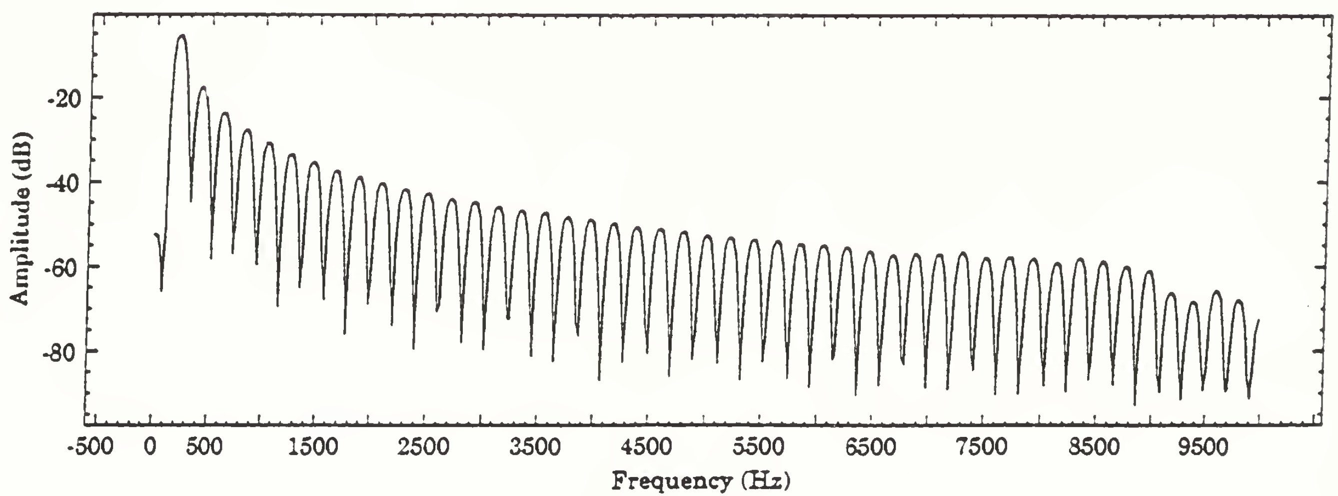

-20
-40
-60
-80
Amplitude (dB)
-500
0
500
1500
2500
3500
4500
5500
6500
7500
8500
9500
Frequency (Hz)

Figure 7

the tube. This was the maximum value of the s.p. that we were able to use for the fundamental mode due to the ringing of the piston when impacted by the shock wave. The spectrum of the waveform is shown in Fig. 7b, where the level of the fundamental corresponds to 0 dB. There are two important points to be taken from this figure. First, s.p. = 1.1 is the highest drive level we could use before shock formation. Second, the waveform in the constant cross section tube is rich in spectral content.

Our ability to predict the spectrum of the waveform is shown in Fig. 8, which is a plot of the Fourier components of the waveforms generated in Tube #1 as a function of strength parameter. The measured values are represented by the symbols. The theoretical results are represented by the solid line. These results agree well with the measured values from the n = 2 down to the n = 4 or even n = 5 harmonic. Note, however, that the observed values are consistently just below the theoretical values. The reasons for these discrepancies are unclear.

Figures 9a and 9b show a waveform and its spectrum for Tube #3 when driven at s.p. = 2.74. Notice the absence of shocks or distortion and the corresponding lack of harmonics in spite of the fact that the s.p. is approximately 2.5 times greater than that in Fig. 7. This demonstrates the fact that introducing anharmonicity into the tube greatly reduces distortion. Further, anharmonicity is highly effective in inhibiting the distortion of standing waves and energy loss from the fundamental. For this tube, practically all (99%) of the total energy is confined to the fundamental. Data for Tube #2 show similar results. Although not shown here, theoretical predictions of the spectra (based on Coppens and Sanders' work) for the waveforms in Tubes #2 and #3 are in very good agreement.

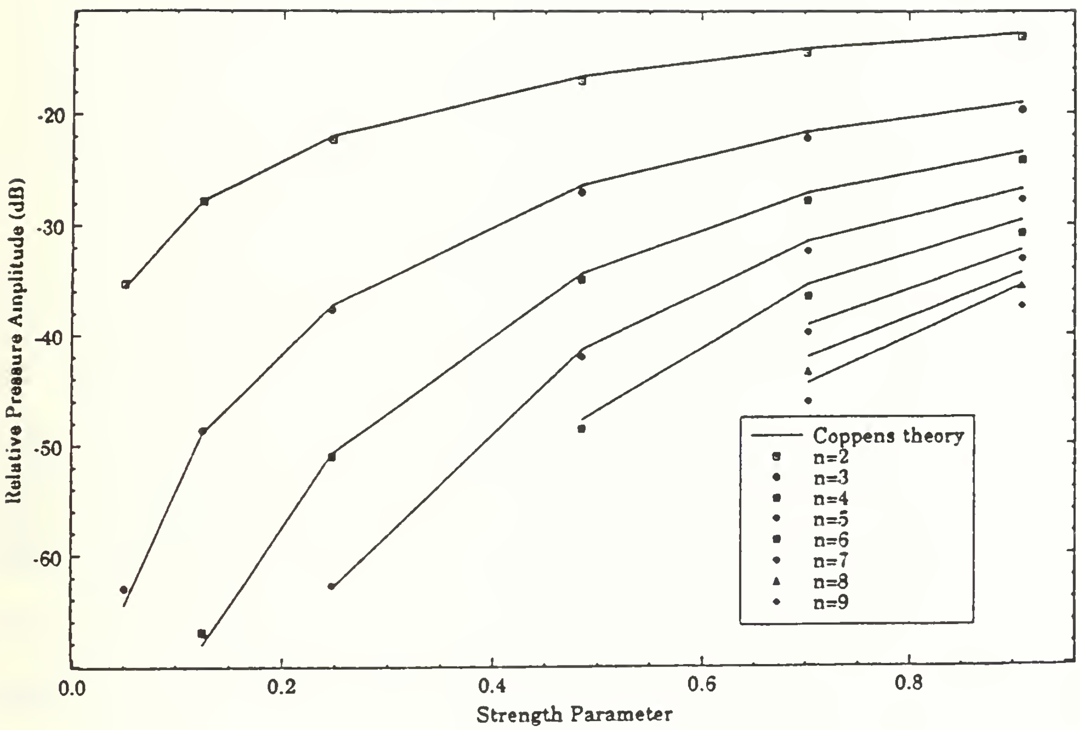

Relative Pressure Amplitude (dB)
-20
-30
-40
-50
-60
0.0
0.2
0.4
0.6
0.8
Strength Parameter
Coppens theory
n=2
n=3
n=4
n=5
n=6
n=7
n=8
n=9

Figure 8

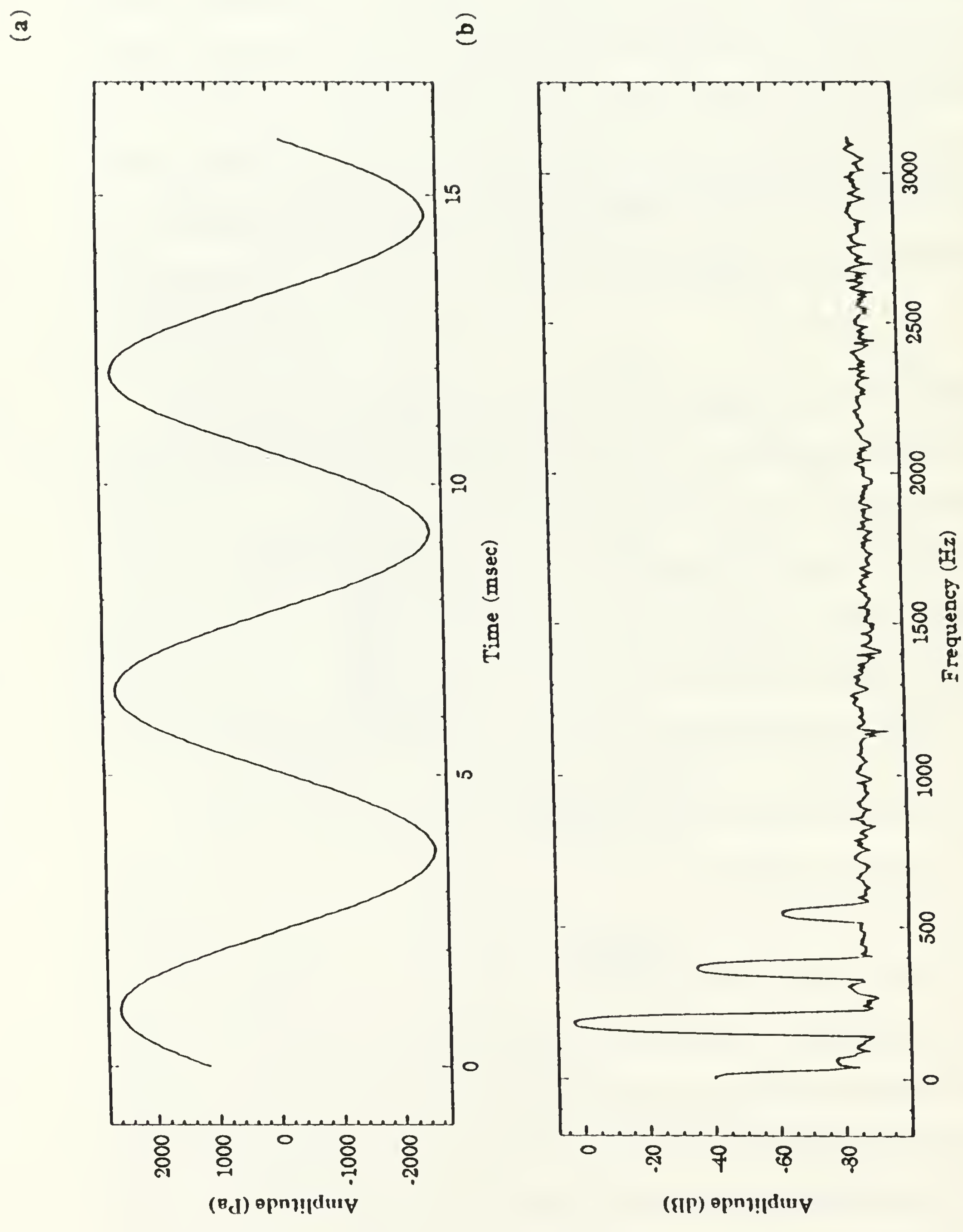

(a)
Amplitude (Pa)
2000
1000
0
-1000
-2000
0
5
10
15
Time (msec)
(b)
Amplitude (dB)
0
-20
-40
-60
-80
0
500
1000
1500
2000
2500
3000
Frequency (Hz)

Figure 9

Two of the three questions raised earlier - Can the nonlinear waveforms be predicted? And, is there a way to prevent input energy being lost from the fundamental mode and transferred to the higher harmonics? - have been answered. We have also shown that Coppens and Sanders' formulation is applicable to anharmonic tubes. One final question remains to be answered - how much of the energy input to the fundamental by the piston is transferred to higher modes?

In our experiment, practically all the input energy is delivered to the fundamental mode. However, in real systems, as we have shown, some of the input energy is transferred to higher modes, becoming thermoacoustically useless. We want to find out how large this effect is. Using the measured spectrum levels, we calculated the energy dissipated through thermal and viscous wall losses in each mode that appears in the spectrum. We then summed the energy dissipated in each mode to find the total dissipated energy. We compared this energy to the energy dissipated by the fundamental alone. The results are shown in Fig. 10, where the ratio of the energy dissipated in the fundamental mode to the total energy dissipated in all modes is plotted as a function of s.p. There is quite obviously a difference between Tube #1 and Tubes #2 and #3. The anharmonicity has a dramatic effect. At a s.p. of approximately 1.4, approximately 18% of the energy delivered to the fundamental of Tube #1 is lost to higher modes, whereas there is practically no energy loss from the fundamental in Tubes #2 and #3, even for s.p. almost twice as high!

This analysis leads to the question "Does the measured energy input equal the total measured dissipated energy?" Figure 11 shows a plot of the percent difference between the total measured dissipated energy and the measured

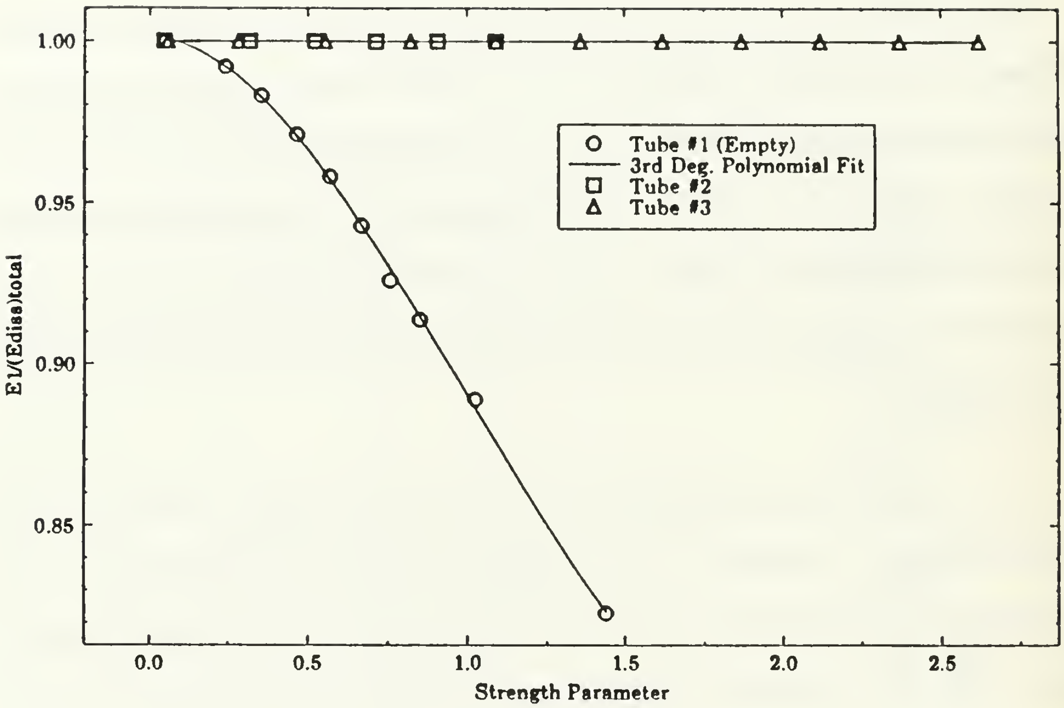


Figure 10

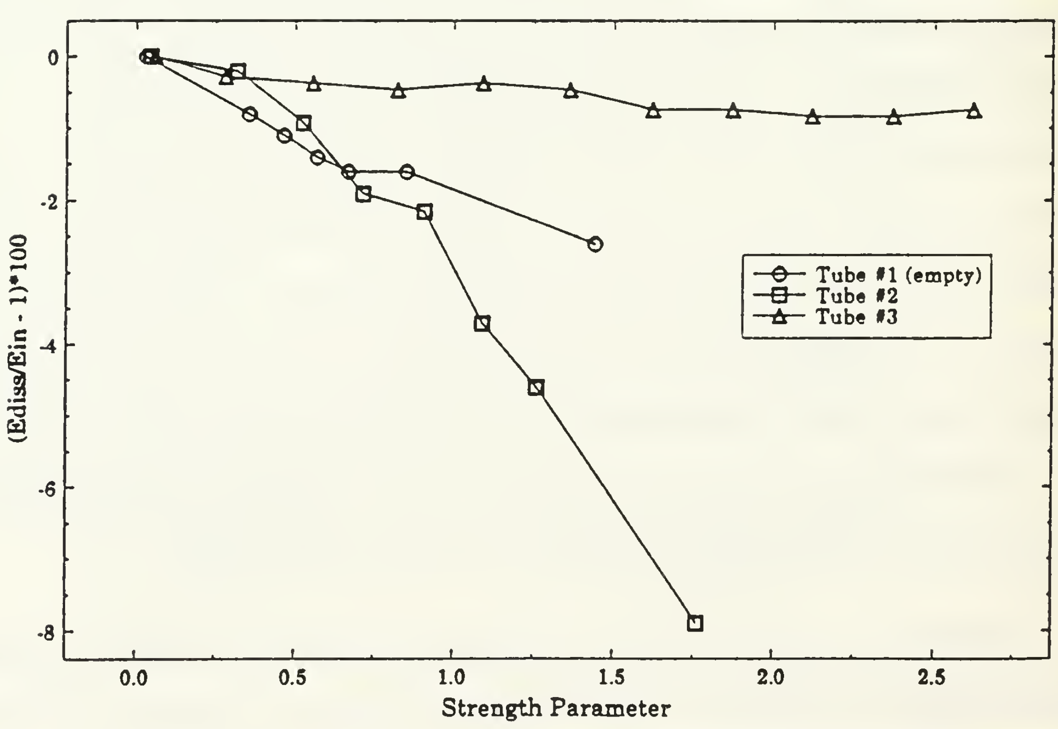


Figure 11

energy input as a function of s.p. The energy input is determined by measuring the piston velocity and the acoustic pressure at the piston. It is seen that for all tubes, practically all of the input energy can be accounted for by acoustic dissipation at the lowest values of s.p. For Tube #3, acoustic dissipation accounts for at least 99% of the energy input for all values of s.p., although there is a slight decrease in the agreement as s.p. increases. For Tubes #1 and #2 the decrease with increasing s.p. is much more dramatic. For Tube #1, the percent difference increases to approximately 2% at the highest s.p. Even though a large number of modes are excited, most (approximately 98%) of the energy is accounted for through acoustic dissipation. With regards to Tube #2, one might have expected it to behave similarly to Tube #3, because the spectra of the waveforms are very similar. However, as seen in the figure it does not. The data indicate that, even though the spectrum contains relatively few components, a significant amount of energy is evidently dissipated nonacoustically. One possible explanation is that the reduced cross section of Tube #2 induces turbulence. It should be recalled that the reduced section is in the center of the tube where particle velocities are highest. The peak velocity amplitude is further increased by the reduced cross section. Tube #3 was designed with an enlarged cross section, so that peak velocity amplitudes are reduced. The mechanisms for the excessive energy dissipation need further attention.

The purpose of this investigation was to extend previous work in finite amplitude standing waves to anharmonic tubes and to consider the transfer of energy from the fundamental to higher modes. We found that Coppens and Sanders' theoretical technique provides a good description of the relative amplitudes of harmonic components of standing waves in both harmonic and anharmonic tubes. Measurements also indicated that as much as 1/5 of the power delivered to a harmonic tube is dissipated in higher modes. It was shown that introducing a variable cross section significantly reduces transfer of energy from the fundamental. In general, for anharmonic tubes, the n = 2 harmonic remains 40 dB below the amplitude of the fundamental. It was also shown that an enlarged cross section is preferable to a reduced cross section, based on comparison of the total power input to the total rate of acoustic energy dissipation.

3) <u>Investigation of Thermoacoustic Engines with Laser Doppler Anemometry</u>

In FY 1991 funds were obtained to acquire a laser Doppler anemometer (LDA) to probe the velocity field of thermoacoustic devices. It was recognized in our FY 1992 research proposal, that it was unlikely that this device would be received and up and running until mid-to-late FY 1992.

The LDA was received this spring. We are currently in the design and fabrication phase of the apparatus for the preliminary measurements. These measurements will consist of studying the velocity field in an empty resonator driven at high acoustic amplitudes. It is worth while mentioning that Van Doren and Hamilton have attempted LDA measurements of acoustic streaming phenomena in high amplitude standing waves.[13] They met with limited success. One thing is definitive from their work however. High amplitude standing wave are replete with complex flow behavior.

4) <u>Investigation of Heat Driven Refrigerators</u>

Investigation of heat driven thermoacoustic refrigerators has been one of the long term goals of our research program. The development of a refrigerator is certainly more applied than most of our previous work. But, because a heat driven refrigerator consists of both a prime mover and a heat pump, it constitutes a much more demanding test of our understanding of thermoacoustics. Although, Wheatley built a prototype device (with which he was able to achieve cold end temperatures below 0 °C) shortly before his death, there has been no subsequent work on this type of device, outside of our laboratory. Aside from the benefits to basic research, this project has the potential for significant benefits to society. Thermoacoustic refrigerators operate well using inert gas as the working fluid rather that environmentally damaging chlorofluorocarbons (CFCs). With a CFC ban drawing ever closer, any alternate technologies should be pursued.

Work in this area during FY 1992 has concentrated primarily on developing analysis techniques that will facilitate design of a refrigerator. Also, construction of a modular prime mover has begun. The flexible design will allow the prime mover to be (relatively) easily modified to convert it to a refrigerator. It is expected that the initial fabrication will be completed by the end of the fiscal year. Measurements should begin in early FY 1993.

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PUBLICATIONS / PATENTS / PRESENTATIONS / HONORS REPORT

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TITLE OF CONTRACT: BASIC RESEARCH IN THERMOACOUSTIC HEAT TRANSPORT

NAME OF PRINCIPAL INVESTIGATOR: ANTHONY A. ATCHLEY

NAME OF ORGANIZATION: PHYSICS DEPARTMENT
NAVAL POSTGRADUATE SCHOOL

ADDRESS OF ORGANIZATION: MONTEREY, CA 93943

****

PAPERS SUBMITTED TO REFEREED JOURNALS
(Not yet published.)

Anthony A. Atchley, "Standing wave analysis of a thermoacoustic prime mover below onset of self-oscillation," J. Acoust. Soc. Am. 92, 2907-2914 (1992).

D. Felipe Gaitan and Anthony A. Atchley, "Finite amplitude standing waves in harmonic and anharmonic tubes," Submitted to J. Acoust. Soc. Am. (1992).

PAPERS PUBLISHED IN REFEREED JOURNALS

Anthony A. Atchley, Henry E. Bass, Thomas, J. Hofler and Hsiao-Tseng Lin, "Study of a thermoacoustic prime mover below onset of self-oscillation," J. Acoust. Soc. Am. 91, 734-743 (1992).

PAPERS PUBLISHED IN NON-REFEREED JOURNALS

N/A

TECHNICAL REPORTS PUBLISHED

Anthony A. Atchley, "Annual summary of basic research in thermoacoustic heat transport: 1991," Naval Postgraduate School Report Number NPS PH-92-003, 35 pages, October, 1991.

BOOKS (AND SECTIONS THEREOF) SUBMITTED FOR PUBLICATION

N/A

BOOKS (AND SECTIONS THEREOF) PUBLISHED

Henry E. Bass, J. Brian Fowlkes and Anthony A. Atchley, "Ultrasonics," Encyclopedia of Science and Technology 6th Edition (McGraw-Hill, New York, 1992).

PATENTS FILED

N/A

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INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

Anthony A. Atchley, "Thermoacoustics," 1992 Physical Acoustics Summer School, Asilomar Conference Center, Pacific Grove, CA, June 24 - July 1, 1992.

CONTRIBUTED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

Anthony A. Atchley, "Standing wave analysis of the low amplitude performance of a thermoacoustic prime mover," 123rd Meeting of the

Acoustical Society of America, Salt Lake City, UT, May 1992, J. Acoust. Soc. Am. 91, No. 4, Pt. 2, 2396(A) (1992).

D. Felipe Gaitan, W. Jerry Lentz, and Anthony A. Atchley, "Further investigation of a single, stable, sonoluminescing bubble using Mie scattering," 123rd Meeting of the Acoustical Society of America, Salt Lake City, UT, May 1992, J. Acoust. Soc. Am. 91, No. 4, Pt. 2, 2331(A) (1992).

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HONORS/AWARDS/PRIZES

Fellow, Acoustical Society of America (1992)

R. Bruce Lindsay Award (Given by the Acoustical Society of America. 1992)

NPS Faculty Performance Award 1991

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